



# Are X-ray properties of loose groups different from those of compact groups?

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## ABSTRACT

We compare the X-ray properties of loose and compact galaxy groups, using a combined sample of 42 groups. We find that we are unable to separate loose and compact groups on the luminosity-temperature relation, the luminosity-velocity dispersion relation or the velocity dispersion-temperature relation using equally weighted errors. This suggests that the distinction between compact and loose groups is not a fundamental one, and we argue that a more useful distinction is that between X-ray bright and X-ray faint systems.

Given their similarity in X-ray properties, we combine the loose and compact subsamples to derive relations based on the full sample. This provides the highest statistical quality results to date on the way in which the correlations in X-ray properties of low mass systems depart from those seen in rich clusters.

**Key words:** Intergalactic medium – X-rays: galaxies

## 1 INTRODUCTION

Many galaxies in the local universe, including the Milky Way, are found in dynamically bound groups. These groups have been divided into two broad types: compact and loose. Compact groups are composed of galaxies separated on the sky by only a few galactic radii, and as such they are more easily identified than the more numerous loose groups, and hence have been intensively studied.

The status of compact groups is still controversial. Such compact configurations of galaxies, with modest velocity dispersions, would be expected to result in galaxy merger rates greater than those observed (?). Simulations of compact groups have shown that the predicted merging rate is reduced if a significant amount of the group mass is contained in a common halo (e.g. ?). Moreover, compact cores could be replenished by continuing infall of new galaxies (?), or could be dense, bound configurations which form temporarily within loose groups (?). Alternatively, the low merging rate would not pose a problem if compact groups were chance alignments within loose groups (?) or filaments seen end on (?), as in these cases the groups would not be as physically compact as they appear.

Recent studies of compact groups which have probed further down the galaxy luminosity function than the data from which the groups were originally identified, indicate

that many compact groups are located within overdense environments (e.g. ?; ?; ?). On the basis of galaxy distribution, there also seem to be different families of compact groups, which may correspond to different dynamical stages of group evolution (?).

An alternative approach to investigation of the evolutionary status of groups, is to study the X-ray emission from the intergalactic medium in these systems. ? carried out an essentially complete survey of the X-ray properties of the Hickson Compact Groups (HCGs), originally identified by ? – the best studied sample of compact groups. The results of this X-ray survey indicated that hot intergalactic gas is found in association with at least 75% of HCGs. This suggests that most of these groups are real gravitationally bound systems.

Diffuse X-ray emission superficially similar to that seen in compact groups, has also been noted in a number of loose groups (?; ?; ?). If compact and loose groups are truly different types of system, or if they represent very different stages of group evolution, then one would expect to see differences in the properties of the intragroup gas, and in particular in the correlations involving X-ray luminosity and temperature, which reflect the relationship between the gas, the potential well, and the galaxies it contains. In this paper we combine the work of ? with the recent survey of X-ray bright loose groups by ? to compare the X-ray properties of loose and compact groups. Throughout this paper we take  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

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## 2 THE SAMPLE

The properties of the compact groups used here are taken from an almost complete survey of the redshift-accordant Hickson compact groups by ?, while the properties of the loose groups are taken from ?. Detailed descriptions of the data reduction and analysis may be found in these papers. ? used a combination of *ROSAT* all-sky survey and pointed data. Point sources were excluded, and a count rate and spectrum extracted within a radius corresponding to 200kpc for all groups, except two in which a larger radius of 500kpc was used. A hot plasma model was fitted to groups with pointed data exceeding a  $3\sigma$  detection limit and luminosities derived using the fitted model. For the RASS data a fixed spectral model was used to derive a luminosity. This gave a total of 22 systems with detected diffuse emission of which 16 had derived X-ray temperatures.

The groups examined in ? are based on pointed *ROSAT* PSPC observations of 24 X-ray bright groups. These systems were originally identified from three different sources, the optical group catalogues of ? and ? were examined to identify 15 X-ray bright groups, and then included were the 9 X-ray bright groups from ?. ? excluded point sources and extracted a count rate and spectrum within a radius determined for each group by examining a smoothed image and group profile. A hot plasma model was then used to obtain a temperature and derive a luminosity. This gave 24 groups all with derived luminosities and temperatures.

Four systems (HCGs 42,62,68 and 90) are common to both samples. Despite the somewhat different procedure used in the two studies, comparison of the derived luminosities show that they typically agree to within 10%, with the temperatures agreeing to within approximately 15%. These are compact groups, and for our analysis below we use the parameters given in ?, although for groups 42,62 and 90 the velocity dispersions used are taken from ?, as the larger number of fainter galaxies they identify results in a more accurate velocity dispersion. The full dataset is shown in Table 1 and consists of 20 loose groups and 22 compact groups, of which a subset of 16 compact groups have temperature measurements.

It should be noted that neither the loose or compact group samples should be regarded as being statistically complete in any way. However, we do not believe that this will introduce any particular bias, other than the fact that since we only use groups with detected diffuse X-ray emission, we do not include systems with undetectably faint intergalactic gas. The two samples could rather be regarded as reasonably representative samples of X-ray bright groups of each type.

## 3 X-RAY CORRELATIONS

The relation between X-ray luminosity and temperature for loose and compact groups is plotted in Figure 1. It is clear that these two parameters are significantly correlated ( $K=5.02$ ,  $P \ll 0.00001$ ) across the sample as a whole. In order to investigate whether there is any significant difference between the relations for the loose and compact subsamples, we perform a linear fit to the  $\log T$ ,  $\log L_X$  data to each subsample, and derive confidence regions for these fits. If these

confidence regions are disjoint then the two sets of groups have significantly different  $L : T$  relations.

In calculating the best fit relations and their errors, the question arises as to whether each data point should be weighted by its statistical error. This is the correct approach provided that points deviate from the mean relation only on account of these statistical errors. For the data shown in Figure 1, the variance about the mean trend is 6 times greater than the variance expected from the statistical errors. This is not surprising as it is clear from cluster studies that there is substantial genuine scatter about the mean relationship (e.g. ?) which is likely to be even more significant for groups (e.g. ?). Under these circumstances, it is clearly not appropriate to use weights based on the statistical error for each point, and we adopt the alternative approach of weighting each point equally, since the variance is dominated by real, rather than statistical, scatter. In reality the variance about the mean trend will be a combination of both real and statistical scatter. We therefore also include the results of statistically weighted fits, for purposes of comparison.

For the equally weighted fits the  $x$  and  $y$  errors for each data point (needed to provide the relative weights of offsets along each axis, and to enable confidence intervals to be calculated) are calculated from the observed scatter about the fitted trend. In order to determine the appropriate weightings we initially fit a regression line to the entire dataset using the ODRPACK package (?) which takes into account the errors in both the  $x$  and  $y$  directions on each point. The scatter about the best fit on both axes was then determined and used as an estimate of the (equal) errors on each point. The data were then refitted with a new regression line and the scatter was again determined. This iteration continued until a stable fit was found.

Table 2 shows the results of the different fits, using the equally weighted errors, and for comparison, the fits obtained using individual statistical errors on each point. The first column lists the relation under consideration and whether each data point was weighted equally or the individual errors on each point were used. The results of fitting a straight line in log space to the compact, loose and combined samples are then shown, along with  $1\sigma$  errors. These errors were derived using ODRPACK, and are based on the statistical scatter of the points about the best fit line. As can be seen, in some cases there are substantial differences in the slopes derived for the relations, depending on how the data points are weighted. For example, the very steep  $L : T$  slope (8.2) obtained by ? using statistical weighting, is due in part to the strong leverage exerted by a small number of the brightest groups, which have the smallest error bars. We believe that the equally weighted results presented here give a more reliable measure of the true correlations.

Confidence regions in the slope:intercept plane have been calculated for the loose and compact subsets, using the equally weighted data. These confidence regions are superposed in Figure 2. As can be seen, there is considerable overlap, with the best fit for each sample lying well within the 90% confidence contour of the other, implying no significant difference between the two datasets. It therefore makes sense to combine the two samples, and we plot in Figure 1 the best fit line and one sigma error bounds for the entire sample with all points weighted equally. Also plotted for comparison is the original relation derived by ? for the com-

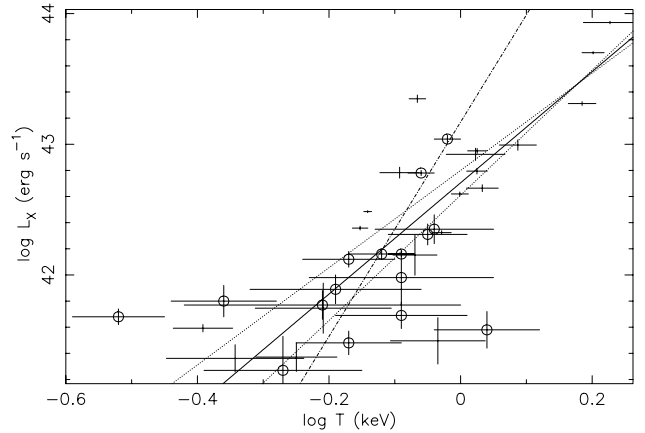
**Table 1.** Properties of the compact and loose groups

Compact groups				Loose groups			
Group name	Temperature (keV)	log L (erg s <sup>-1</sup> )	velocity dispersion km/s	Group name	Temperature (keV)	log L (erg s <sup>-1</sup> )	velocity dispersion km/s
HCG12	0.89±0.12	42.31±0.08	269±99	NGC315	0.85±0.07	42.15±0.15	122±43
HCG15	0.44±0.08	41.80±0.12	457±147	NGC383	1.53±0.07	43.31±0.02	466±48
HCG16	0.30±0.05	41.68±0.06	135±62	NGC524	0.56±0.08	41.37±0.11	205±51
HCG33	0.61±0.30	41.77±0.11	174±80	NGC533	1.06±0.04	42.95±0.02	464±55
HCG35	0.91±0.18	42.35±0.11	347±112	NGC741	1.08±0.06	42.66±0.03	434±48
HCG37	0.67±0.11	42.12±0.06	447±165	NGC1587	0.92±0.15	41.50±0.18	106±38
HCG42	0.82±0.03	42.16±0.02	211±36	NGC2563	1.06±0.04	42.79±0.02	336±42
HCG48	1.09±0.21	41.58±0.14	355±212	NGC3607	0.41±0.04	41.59±0.03	421±172
HCG51	-	42.99±0.11	263±97	NGC3665	0.45±0.11	41.36±0.10	29±10
HCG57	0.82±0.27	41.98±0.21	282±84	NGC4065	1.22±0.08	42.99±0.04	495±101
HCG58	0.64±0.19	41.89±0.11	178±66	NGC4073	1.59±0.06	43.70±0.01	607±94
HCG62	0.96±0.04	43.04±0.03	376±49	NGC4261	0.94±0.03	42.32±0.02	465±57
HCG67	0.82±0.19	41.69±0.10	240±110	NGC4325	0.86±0.03	43.35±0.03	256±47
HCG68	0.54±0.15	41.27±0.26	170±63	NGC4636	0.72±0.01	42.48±0.01	463±95
HCG73	-	42.43±0.24	95±57	NGC5129	0.81±0.06	42.78±0.04	294±41
HCG82	-	42.29±0.14	708±326	NGC5171	1.05±0.11	42.92±0.05	424±84
HCG83	-	42.81±0.12	501±185	NGC5846	0.70±0.02	42.36±0.02	368±67
HCG85	-	42.27±0.10	417±192	NGC6338	1.69±0.16	43.93±0.01	589±235
HCG86	-	42.32±0.14	302±139	NGC7619	1.00±0.03	42.62±0.02	253±96
HCG90	0.68±0.12	41.48±0.09	193±35	NGC7777	0.62±0.15	41.75±0.20	116±41
HCG92	0.75±0.08	42.16±0.04	447±206				
HCG97	0.87±0.05	42.78±0.02	407±150				

compact group sample, in which the errors on each individual point were used. This relation is clearly too steep because two points (HCG62 and HCG97) have very small errors and significantly steepen the line (c.f. the equally weighted compact group sample in which the slope is 3.6). It should be noted that although the slope of the fit to the compact group sample is much flatter using equally weighted errors compared to using individual statistical errors, the lines fitted to the compact and loose group samples are statistically equivalent using either type of error (see Table 2).

The relationship between X-ray luminosity and group velocity dispersion is also examined in an identical way to the  $L : T$  relation. Table 2 shows the results of the different fits to the whole  $L : \sigma$  dataset and the separate loose and compact subsamples. Maps of  $\chi^2$  were produced for the two subsamples and once again a clear overlap is seen in the confidence regions (Figure 3).

The relationship between X-ray luminosity and velocity dispersion for the full sample is plotted in Figure 4. The correlation between these parameters is strong ( $K=3.92$ ,  $P=0.0001$ ), and also shown are the best fit individually weighted (dashed line) and equally weighted (solid line) fits to the data. As can be seen there is a very significant difference between the two lines. There is one point with a very low velocity dispersion (NGC 3665, 29 km s<sup>-1</sup>) which stands out on this graph. A virialised system must have a minimum mean density related to the density of the universe which can be used to constrain the velocity dispersion of a virialised group to be greater than 100 km s<sup>-1</sup> (?). A velocity dispersion of 29 km s<sup>-1</sup> clearly lies below this

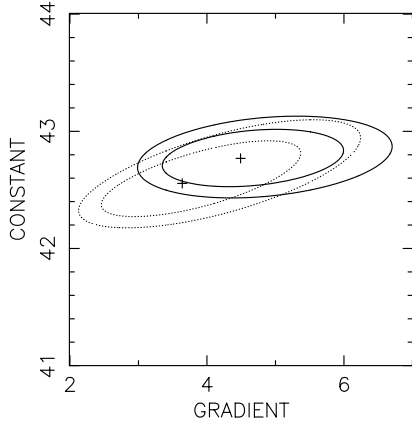


**Figure 1.** Relation between X-ray luminosity and temperature for the combined compact (crosses with central circles) and loose (plain crosses) group samples. The bold line is best equally weighted fit to whole sample with 1  $\sigma$  error bounds marked with dotted lines. The dash-dot-dash line is best fit to compact group sample using individual errors.

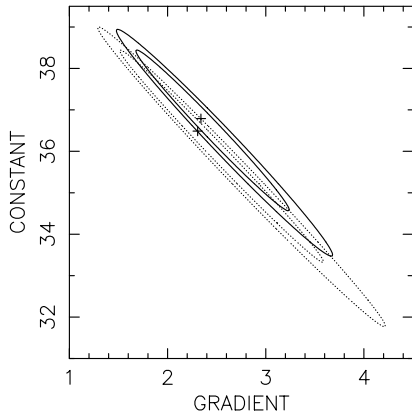
limit. Given that the X-ray emission suggests a collapsed system, the real velocity dispersion of the system is likely to be much higher than has been measured from the four catalogued members. Exclusion of this point has a significant effect on the gradient of the equally weighted line, increas-

**Table 2.** Results of fits to the compact, loose and combined samples. Each fit is based on a straight line fit in log space. The best fits for the full dataset based on the equally weighted approach are marked in bold. <sup>a</sup> indicates all points were weighted equally, <sup>b</sup> indicates that individual errors on each point were used. Errors are  $1\sigma$ . †This fit is noticeably affected by one discrepant point. Exclusion of this point steepens the slope to 2.9, as discussed in the main text.

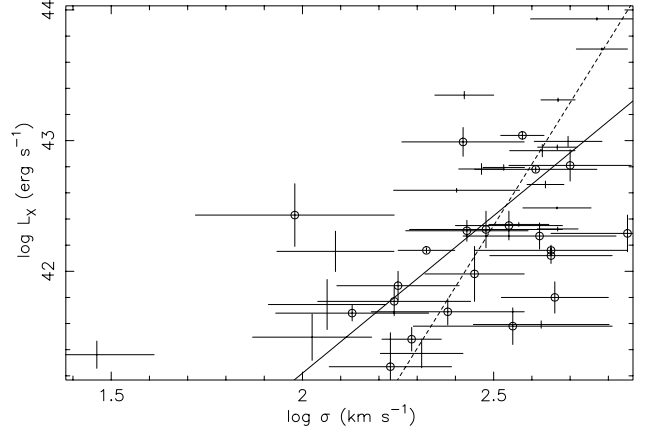
relation	compact groups		loose groups		full sample	
	gradient	intercept	gradient	intercept	gradient	intercept
L:T <sup>a</sup>	3.6±0.9	42.5±0.2	4.5±0.6	42.8±0.1	<b>4.3±0.5</b>	<b>42.7±0.1</b>
L:T <sup>b</sup>	8.2±2.7	43.17±0.26	4.5±0.8	42.95±0.09	5.0±0.7	43.01±0.07
L:σ <sup>a</sup>	2.3±0.6	36.5±1.6	2.3±0.5	36.8±1.1	<b>2.4±0.4 †</b>	<b>36.4±1.0</b>
L:σ <sup>b</sup>	4.9±2.1	30.0±5.1	4.6±1.4	31.0±3.6	4.7±0.9	30.6±2.3
σ:T <sup>a</sup>	1.4±0.3	2.64±0.06	1.9±0.5	2.55±0.08	<b>1.7±0.3</b>	<b>2.60±0.05</b>
σ:T <sup>b</sup>	0.9±0.3	2.55±0.05	1.1±0.3	2.57±0.03	1.0±0.2	2.57±0.03



**Figure 2.** Confidence regions of straight lines fitted in log space to the equally weighted L:T data of compact (dotted) and loose (solid) groups. The crosses mark the best fit to each subset. Contours are  $1\sigma$  and 90% confidence.



**Figure 3.** Confidence regions of straight lines fitted in log space to the equally weighted L:σ data of compact (dotted) and loose (solid) groups. The crosses mark the best fit to each subset. Contours are  $1\sigma$  and 90% confidence.



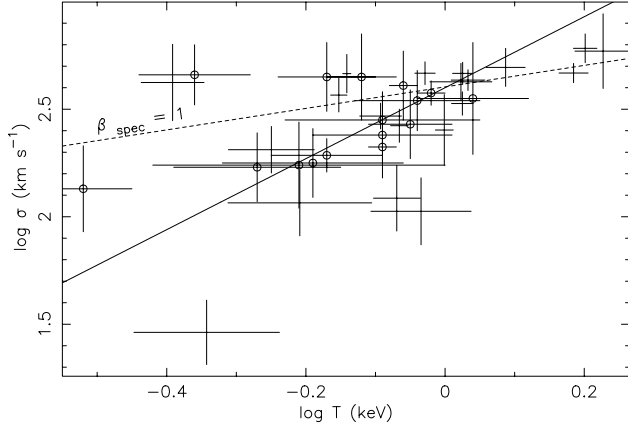
**Figure 4.** Relation between X-ray luminosity and velocity dispersion. Data symbols are same as in Figure 1. The solid line shows best fit equally weighted line to whole sample and the dashed line shows individually weighted fit to whole sample.

ing the slope to 2.9 which is within  $2\sigma$  of the individually weighted line.

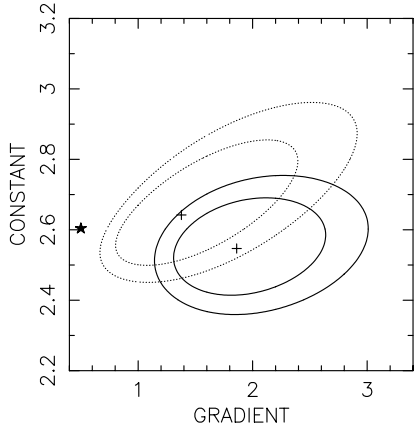
The relationship between velocity dispersion and temperature is shown in Figure 5. Once again a series of fits are carried out on the samples (Table 2) and the  $\chi^2$  maps (Figure 6) show significant overlap. Also plotted on Figure 5 is the equally weighted regression line and the line for  $\beta_{spec} = 1$ , where  $\beta_{spec}$  is the ratio of the specific energy in the galaxies to that in the gas. The locus  $\beta_{spec} = 1$  is plotted on Figure 6 and clearly shows that  $\beta_{spec} = 1$  is a poor fit to both subgroups of data.

#### 4 DISCUSSION AND CONCLUSIONS

As can be seen from the  $\chi^2$  maps for each of the three relations, the compact and loose group data do not appear to differ significantly. The best fit for each subset (compact/loose) always lies within the 90% confidence region of the other subset, and there is much overlap of the  $1\sigma$  confidence regions. Although there are some differences in the regression lines obtained when using statistically or equally weighted errors, the compact and loose group samples are



**Figure 5.** Relation between velocity dispersion and temperature. Data symbols are same as in Figure 1. The solid line shows best fit equally weighted line to whole sample and the dashed line shows the line  $\beta_{spec} = 1$ .



**Figure 6.** Confidence regions of straight lines fitted in log space to the equally weighted  $\sigma:T$  data of compact (dotted) and loose (solid) groups. The crosses mark the best fit to each subset. The solid star marks the position of  $\beta_{spec} = 1$ . Contours are 1  $\sigma$  and 90% confidence.

still equivalent to one another when using either type of error (see Table 2). The X-ray surface brightness profiles of compact galaxy groups (e.g. ?; ?; ?; ?) are also comparable with those derived for loose groups (?) and are flatter than those observed in galaxy clusters, providing further evidence that compact and loose groups are similar systems.

Given this similarity, the results shown in bold in Table 2, derived from the full sample of 42 groups, represent the best estimates available of these relations for galaxy groups. Though, as discussed in section 3, the slope of the  $L : \sigma$  relation given in the Table is biased low by one outlying system which probably has an incorrect velocity dispersion. These results are derived using the equally weighted errors which should be more reliable than using individual statistical errors, given the observed scatter in the relationships.

The steepening of the  $L : T$  and  $\sigma : T$  relations in low temperature systems support preheating models (see ? for

more details), in which injection of energy from the epoch of galaxy formation lowers the density and raises the temperature of the intergalactic gas in galaxy groups. Models of this process (?; ?) predict that the mass-temperature relation should rapidly steepen at a temperature related to the temperature to which the gas was preheated. As  $M \propto \sigma^2$  we should also see this effect as a steepening of the  $\sigma : T$  relation, as is observed below  $T = 1$  keV in Fig.5. Also noticeable is the large scatter about the mean trends in all three of the correlations examined here – especially in the poorest systems. This finds a natural interpretation in terms of the variation in detailed evolutionary history in such sparse systems, between one group and another.

What implications for the relationship between compact and loose groups follow from the apparent indistinguishability in their X-ray properties? One possibility is clearly that compact groups are simply fortuitous alignments of galaxies within loose groups (?) – however the accumulation of data showing clear evidence for strong galaxy interactions within HCGs has convinced even most sceptics that many of them are genuinely dense in three dimensions (?). On the other hand, the results presented above, in conjunction with deep optical surveys showing much more extended distributions of galaxies associated with compact groups (?; ?; ?), argue that they are not fundamentally different from loose groups.

This apparently leaves two viable models for the nature of compact groups. In the model of ?, compact groups are temporary bound configurations which form within loose groups, whilst ? propose a model in which compact cores are regenerated by continuing infall of galaxies, whilst merger rates are reduced by halo stripping of the group members. The model of ? appears to conflict with the observed X-ray properties of compact groups. In the simulations presented by these authors, compact groups are produced at a variety of locations within their natal loose group, during its evolution. The majority of these temporary bound groupings do not occur at the centre of the main group. In this case, one would expect that compact groups would frequently be offset from the X-ray centroid associated with the core of the larger potential well of the group as a whole. This is not what is observed. X-ray studies show that HCGs associated with X-ray emission are invariably at the core of that emission.

The model of ? appears to account well for the observed properties of X-ray bright compact groups, and for the fact that they are embedded within looser overdense configurations. The fact that such X-ray bright systems invariably contain a fairly bright early type galaxy near their centre is explained in this model as the result of early merging activity in the collapsing group core. The existence of X-ray bright loose groups with essentially identical X-ray properties follows immediately from the fact that such systems only satisfy the isolation and compactness criteria required of compact groups for a fraction of the time.

There is, however, a second type of compact group, which cannot be accounted for by the model of ?. These groups are not dominated by an early type galaxy, they may show signs of galaxy interactions in the optical (?) or HI (?), but they show either weak or no diffuse X-ray emission ( $L_X < 10^{42}$  erg s $^{-1}$ ), and they typically have lower velocity dispersions than the X-ray bright groups. ? suggest that such systems (their “core+halo” and “compact” classes) may be

in a more advanced evolutionary state than the systems which represent the cores of more extensive loose groups. However, the common association of extensive hot gas halos with the latter class of groups shows that this cannot be the case. There is no way that systems like HCG42, HCG62 and HCG97 can lose their X-ray bright halos as their evolution proceeds, so they cannot evolve into X-ray faint systems like HCG16. Also the fraction of ellipticals and velocity dispersion are typically higher in the X-ray bright systems, and these are most unlikely to drop as the system evolves.

It seems that either the X-ray faint groups (both loose and compact) are an *earlier* evolutionary stage, or they are simply different from the X-ray bright systems. Their low X-ray luminosity suggests that either these systems have, like the Local Group, not yet collapsed (so that their intergalactic gas has not been compressed to the point where it emits detectable X-ray emission), or that their potential wells are too shallow to concentrate preheated gas sufficiently to achieve a detectable X-ray surface brightness. In the case of compact groups in which strong galaxy interactions are seen, it is clear that the core of the system must have collapsed to a dense state, so the second effect must be the dominant one.

## 5 ACKNOWLEDGEMENTS

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